NUMERICAL SIMULATIONS OF CONVECTION IN EUROPA'S ICE SHELL: IMPLICATIONS FOR SURFACE FEATURES.
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Summary: Europa's icy surface displays numerous small (5-30 km-diameter) pits, spots, and uplifts with topography of 100-300 m [1-5]. Although several formation models exist for these features, the most popular is that they result from deformation of the lithosphere by convection in the underlying ice [1,2,6,7,13]. However, it is unclear whether convection can produce topography of the appropriate wavelength, height, and surface expression. Here we present numerical simulations of convection in Europa's ice shell including temperature-dependent viscosity and tidal heating. Ice shells 15 and 50 km thick are considered, consistent with several estimates of the shell thickness on Europa [8-10]. The convection produces 100-200 m-deep pits with 10-20 km diameter–consistent with some of the observed features– when the lithospheric viscosity is 10^3–10^5 times greater than that of the underlying ice, but greater or smaller viscosity contrasts lead to topography insufficient to explain the observed pits and uplifts. When compared with plausible lithospheric stiffnesses, the results suggest that Europa's widest pits and uplifts could result from convection; however, features with diameters < 5 km require other formation mechanisms. The convection induces stresses > 1 bar, which exceeds the inferred strength of Europa's crust [11] and indicates the likelihood of surface disruption.

Introduction: Europa's dominant terrain types are the ridged plains, which consist of successive generations of overprinted ridge pairs, and the chaos terrains, which are comprised of hummocky material and disrupted crustal blocks. In addition, numerous small (< 30 km) landforms were imaged by Galileo, including pits, domes, platforms, irregular uplifts, irregular lobate features, and smooth, flat regions embaying topographic lows. Furthermore, several of the depressions and uplifts alter the topography of the existing surface without disruption. Pappalardo et al. [1] and others suggested that Europa's ice shell undergoes solid-state convection vigorous enough to flex, and perhaps fracture, the lithosphere, producing the observed landforms. However, these ideas have until recently remained qualitative, and it is unclear whether convection can produce enough topography to explain the observed features.

Here we present two-dimensional numerical simulations of solid-state convection in Europa's ice shell with the goal of determining implications for the surface features, especially the amplitude and wavelength of topography produced by the convection.

Model and Methods. We used the Conman finite-element code to solve the incompressible (Boussinesq) fluid equations neglecting inertia, as appropriate to a viscous, slowly convecting system. The boundary conditions are periodic on the sides and free-slip rigid walls (maintained at constant temperature) on the top and bottom. The layer thickness is varied between 10 and 100 km and the Rayleigh number (evaluated using the viscosity at the base) ranges from 10^5 to 10^8.

The rheology is purely viscous with a Newtonian temperature-dependent viscosity relevant for ice:

$$\eta = \eta_0 \exp\left[A\left(\frac{T_m}{T} - 1\right)\right] \tag{1}$$

where T is temperature, T_m is melting temperature, and η_0 is the viscosity at the melting temperature.

The viscosity contrast χ, defined as the ratio between the maximum and minimum viscosities in the simulation, is a free parameter that we vary from 10^2–10^{10}. The value of A is maintained constant at 26. When Eq. (1) implies a local viscosity less than $\chi\eta_0$, that viscosity is used, but when the viscosity predicted by Eq. (1) exceeds $\chi\eta_0$ then the local viscosity is set equal to $\chi\eta_0$.

Internal tidal heating is included. In one set of simulations, the volumetric tidal heating rate Q was held constant, with a value between 10^{-7} and $10^{-4}\,\mathrm{W\,m}^{-3}$. In another set of simulations, Q was determined by the Maxwell model, leading to a strong temperature dependence, with Q maximizing at or near the melting temperature.

The normal stress at the top and bottom boundaries is nonzero and can vary spatially due to fluid-dynamical interactions; in a system with an open top surface, this would produce surface topography proportional to the normal stress. This fact has led to a standard prescription in the Earth mantle convection literature for calculating dynamic (i.e., convectively generated) topography, which we follow here. The surface topography is calculated from from the relation

$$h = \frac{\sigma_{zz}}{\Delta\rho\, g} \tag{2}$$

where h is the topography, σ_{zz} is the vertical component of normal stress, $\Delta\rho$ is the density contrast across the interface (here equal to density itself), and g is gravity.

The simulation was initialized with a conductive temperature profile containing a weak perturbation.

Results. Consistent with analytical estimates [12], our simulations indicate that vigorous convection can occur in ice layers thicker than ~ 15 km. Fig. 1 shows the temperature and dynamic topography resulting from a simulation with a viscosity contrast of 10^4, layer thickness of 50 km, melting-point viscosity η_0 of 10^{13} Pa sec, constant tidal heating rate of $10^{-7}\,\mathrm{W\,m}^{-3}$, and Rayleigh number of 4.3×10^8. Intense downwellings and weak upwellings occur, consist with the fact that the system is internally heated. Depressions 10–20 km wide and ≥ 100 m deep dominate the topographic expression. Their widths are determined not by the depth of the convecting system but by the width of the downwellings (which underlie the depressions).

In contrast, simulations with viscosity contrasts $\leq 10^2$ or $\geq 10^6$ have insufficient topography to explain the observed

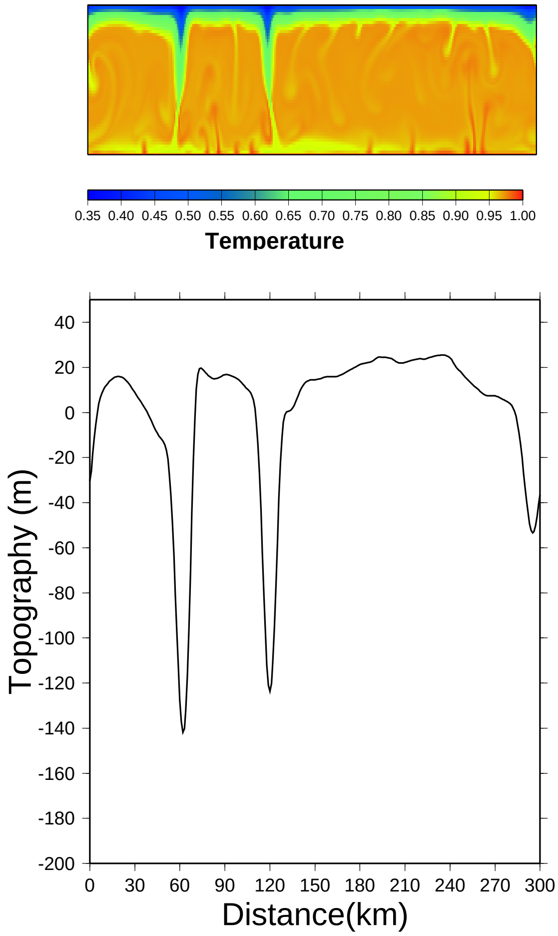

Figure 1: **Top.** Temperature divided by melting temperature for a simulation in a domain 300 km wide and 50 km deep. **Bottom:** Dynamic topography for the same simulation. See text for details.

depressions and uplifts (Fig. 2). In the former case, the density contrasts within the convection are not large, leading to small topography. In the latter case, the thick stagnant lid acts as a filter that inhibits high-amplitude surface topography even when internal density contrasts within the convecting region are large.

Conclusion: Our simulations show that substantial (100-200 m) topography can result from convection in Europa's ice shell if the brittle layer is thin and the convecting regions penetrate within 1–2 km of the surface. In our simulations this occurs for viscosity contrasts of 10^3–10^5. However, simple prescriptions such as Eq. (1) predict that unfractured ice at Europa's 120-K surface temperature has a viscosity $> 10^{10}$ times that of the warmer underlying ice. The real situation is more complex, however, because brittle as well as viscous deformation can occur, and this could broaden the range of viscosity contrasts that allow topography. In fact observational evidence indicates that Europa's crustal strength is < 1 bar [11]. Because convective stresses can exceed 1 bar, brittle deformation may play a role in the convection.

The fact that the convective stresses exceed the inferred strength of Europa's crust indicates that surface disruption, and formation of chaos, could accompany the convection.

The topography in our simulations is dominated by pits rather than uplifts, which results directly from the predominance of downwellings and relative weakness of upwellings. This situation contrasts with conceptual [1] and analytical [7] models suggesting that positively buoyant diapirs can produce localized domes. Furthermore the topographic features generated by our simulations always have diameters exceeding 10 km. Our simulations suggest that convection could produce some of Europa's widest observed pits and uplifts, but the numerous small (< 5 km-diameter) features that exist on the surface [5] require other formation mechanisms.

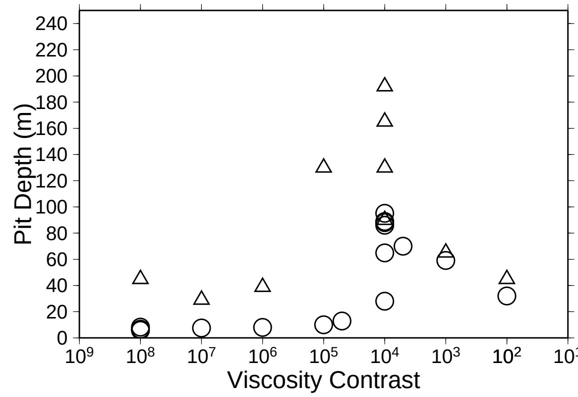

Figure 2: Summary of depth of pits produced by the convection as a function of the viscosity contrast used in the simulations (i.e., the ratio between the maximum and minimum viscosities). Circles and triangles denote simulations with depths of 15 and 50 km, respectively.

References:

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